

# Cosmological dinosaurs

V. K. Dubrovich

*St. Petersburg Branch of Special Astrophysical Observatory,  
Russian Academy of Sciences, 196140, St. Petersburg, Russia and  
Nizhny Novgorod State Technical University n. a. R. E. Alekseev,  
LCN, GSP-41, N. Novgorod, Minin str. 24, 603950*

S. I. Glazyrin\*

*Institute for Theoretical and Experimental Physics, Moscow, Russia*

The hypothesis of existence of primordial black holes with large masses ( $\geq 10^6 M_\odot$ ), formed at the earliest stages of the Universe evolution, is considered in the paper. The possibility does not contradict some theories, see e.g. [1], and may match new observational data. In particular, this scenario of evolution could describe some peculiarities in distant galaxies and quasars. Calculations of evolution of central body mass in protogalaxies for different initial conditions are presented. It is shown that the sufficient rate of BH mass growth is not achieved in the standard scheme without complex additional assumptions. Moreover, the appearance of a primordial black hole in the epoch of primordial nucleosynthesis could significantly change the chemical composition around it. This can lead to different exotic stars with low mass and nonstandard metals enrichment. The proposed scheme is not considered as universal. On the other hand, if only tiny part of existed objects have the considered nature, it gives a unique possibility to study extremal stages of matter and fields evolution in our Universe.

## I. INTRODUCTION

This paper considers the possibility of existence of rare high-redshift objects: galaxies and quasars, formed much earlier than the typical composition of the Universe. We also propose the mechanism of the formation of such objects.

Today the theory of formation of the structure of the Universe is well confirmed by observations. It describes the whole history of our world evolution. Observations cover only tiny part of it: they are limited now to the redshift range  $0 < z < 10$  (see refs. [2, 3]) and the point  $z \approx 1000$  (CMB observations). Modern and future missions and experiments have the possibility to expand the region towards the moment of the Universe creation. On this way we are discovering now more and more distant galaxies with no end in sight. The theory tells us that everything around was built in evolutionary way: for some period after recombination there was no source of light in the Universe – Dark Ages, firsts stars appeared approximately at  $z \approx 30$ , and only further galaxies were constructed. So the observational trend of discovering new objects (galaxies and quasars) should be violated at some redshift. At this point we expect the discovery of something beyond standard predictions.

But what if we find a galaxy so old that it lies beyond the redshift region allowed by the standard theory (ST)? Then something in our understanding needs changing. We consider the theory to be generally correct, that is the number of such extraordinary objects is negligible. But it requires small additions to be applied. We propose

primordial big black holes (PBBHs) as simple candidates to such extension. By this term we mean black holes with masses  $M > M_\odot$  formed in the early Universe (before recombination). In this case we only change the initial conditions for the problem of structure formation. The result could account for the early formation ( $z_{\text{formation}} \gg 30$ ) of rare objects (we propose to call them “cosmological dinosaurs”). We state that it may be not so fantastic: recently two galaxies with unusually high black hole-to-bugle mass ratio were discovered by [4], and a discovery of a star with very low metallicity, see [5]. These examples offer difficulties for the theory. They are candidates for “dinosaurs”.

The structure of the paper is the following. In the Section II the standard theory of the structure formation is considered along with some its bottlenecks. The Section III considers the question of supermassive black holes growth. We show that the creation of a SMBH evolutionary (and after recombination) is not a simple problem even for known today quasars. We consider their masses as a simple general criterium for the dinosaurs: too massive BH in the early Universe could not be described by the standard theory. The general aim of this article is to introduce the concept of cosmological dinosaurs and show that there could be need in some cases. Further works will consider this possibility more carefully.

## II. THE STANDARD THEORY OF STRUCTURE FORMATION

Let us consider the history of the Universe along lines of the standard theory, for good review see [1]. The first relevant stage is inflation. It is inflation that generated fluctuations of matter density and gravitational waves re-

---

\*Electronic address: glazyrin@itep.ru

sponsible for the creation of all astronomical objects. The earliest experimental evidence of these fluctuations available today are observations of CMB temperature spatial distortions. They reflect the state of the Universe at the epoch of the recombination, for recent results see [6] (the future relic neutrino telescopes will make it possible to observe the Universe at the moment much earlier,  $t \approx 1$  s after the Big Bang). According to them the density variations at  $z \approx 1000$  were at the scale of  $\delta\rho/\rho \sim 10^{-5}$ . The standard theory assumes existence of only these perturbations, which are quite uniform.

After the recombination the general contribution to the evolution of the Universe is created by matter, which is composed of DM and baryonic matter. The difference between two components is due to existence of thermodynamic pressure in baryonic component. It leads to the notion of the Jeans wavelength for baryons:

$$\lambda_J = \left( \frac{\pi c_s^2}{\rho_b G} \right)^{1/2}. \quad (1)$$

This length separates oscillatory and exponential growth of linear density perturbations. In case of efficient cooling the Jeans mass  $M_J \sim \rho \lambda_J^3$  defines the mass of an object that contracts and becomes gravitationally bound.

The reality is a slightly more complex. The cold dark matter collapses first and creates potential wells. Baryonic matter accretes into these potential wells. Cosmological hydrodynamic simulations like in [7] are required to fine reconstruct the process of structure formation. The simple analytic consideration from [1] shows that Jeans mass introduced earlier and a minimum halo mass in potential wells agree quiet well.

Together with the first collapsed objects low metallicity PopIII stars appeared. These stars are quiet massive  $M \sim 10^2 \div 10^3 M_\odot$  with small lifetime, see [8, 9]. Their appearance considerably change the evolution of the ambient matter. In the absence of metals (and low temperatures  $T < 10^4$  K) the molecular hydrogen is the most efficient coolant. First stars on the one hand destroyed  $H_2$  with their radiation, on the other hand they started to enrich the Universe with metals ( $Z > 2$ ). Powerful supernova explosions, a typical final stage of PopIII stars evolution, spreaded these elements all over the Universe.

As was mentioned earlier only sophisticated hydrodynamical simulations which take into account star formation and feedback effects could give quantitative answers on galaxies formation for redshifts when nonlinear evolution starts (see [10]). Recent results for the standard theory could be found in works by several groups: [11–13].

Results of cosmological observations can be gathered in the following statements. The candidate for the most distant galaxy known today is located at  $z \approx 10$  [3], but the resolution do not permit yet to determine exact parameters of this object. Most distant confirmed galaxy is at  $z = 8.6$  [2]. And at  $z = 7 \div 8$  there are a lot of galaxies with well known characteristics presented in

[14]. It can be seen from mentioned works that the theory satisfy these observational “restrictions”.

We can’t rule out the case that future observations may find objects that are not confirmed by the standard theory. We can state that these objects, if exist are very rare. To account for such probable discoveries there are two variants of explanations: peculiar point(s) in initial perturbations or our poor understanding of nonlinear evolution of these perturbations.

Let us start with the second variant. The chief process that determines the speed of structure formation is cooling. In the regions with intensive cooling objects are formed earlier. We believe that we know all mechanisms of cooling and relevant physics, so for efficient cooling we need high temperatures  $T > 10^4$  K or abundance of metals. Immediately the question arises: how this region appears? But from the point of view of the evolutionary hypothesis of our world appearance, we cannot create such cosmological peculiarity without peculiarity in initial conditions. So we came to the first variant.

According to the inflationary scenario the Universe was initially created at the Planck length  $l_P$ , which was then exponentially expanded during the inflation stage (this is the general argument explaining homogeneity). There is a variety of inflationary scenarios each with own consequences for our world. Because of the absence of observational experiment in that region of cosmic time everything that satisfy only CMB restrictions could be created. Possibilities for peculiar conditions are wide: from nontrivial topological solutions to new types of particles. These “peculiar objects” should satisfy the following conditions not to be forgotten and influence the evolution of parts of the Universe at  $z \sim 10 \div 100$ . This object should be massive enough  $\geq M_\odot$  or have the possibility to grow in mass. It should be long living  $t \sim t_{\text{recomb}}$ , otherwise the energy deposition by its decay will be spread over large region of space by photons and became non-significant.

The most suitable candidates for initial conditions perturbations are primordial big black holes. The possibilities of their creation have been considered in many papers, for a review see [15]. The key advantage of BH is their possibility to grow in mass and size. It make possible for them to influence large spatial volume. Also the nucleosynthesis near BHs will proceed differently with bigger yield of metals. It lead to faster cooling during the Dark Ages and earlier matter collapse. From our point of view this is the best and the least exotic candidate that could account for “dinosaurs”.

### III. SUPERMASSIVE BLACK HOLE FORMATION

Let’s consider the question of the supermassive black hole formation move carefully. Their existence at definite redshift is a very simple and robust criterium for the validity of the ST. The most distant quasar known today

is located at  $z = 7.085$  with a mass  $M \approx 2 \times 10^9 M_\odot$ , see [16]. We will show that this fact creates some difficulties for the theory that accounts for explanation of the structure formation.

We will make some analytical estimations here and discuss the growth of a hypothetical black hole. The rate of matter falling on the BH could be written in general as

$$\dot{M}_{\text{BH}} = \mu m_p n \sigma v_{\text{matter}}, \quad (2)$$

where  $\mu$  – is an average atomic weight of matter,  $v$  – its velocity,  $n$  – concentration of matter around the BH,  $\sigma$  – cross-section of capture. In case matter is virialized, that is its velocity coincides with the thermal energy and is described by the temperature  $k_B T_{\text{vir}} \sim \mu m_p v^2$ . For this case the cross-section of capture is defined by the Bondi radius:

$$R_{\text{Bondi}} = \frac{\mu m_p G M_{\text{BH}}}{k_B T}. \quad (3)$$

As a result the accretion on the black hole is described by the Bondi–Hoyle formula from [17]:

$$\dot{M}_{\text{Bondi}} = \frac{\alpha 4\pi G^2 M_{\text{BH}}^2 m_H n}{c_s^3}, \quad (4)$$

where the dimensionless parameter  $\alpha = (3\gamma^3)^{1/2}/4 = 0.93$ .

The crucial parameter for the accretion rate is  $n$ . From trivial consideration of a halo with mass  $M_{\text{halo}}$  and radius  $R_{\text{halo}}$  it is equal:

$$n = \frac{3}{4\pi R_{\text{halo}}^3} \frac{M_{\text{halo}}}{\mu m_H} = 4.6 \times 10^{-2} \mu^{-1} R_{\text{halo},6}^{-3} M_{\text{halo},9} \text{ cm}^{-3}. \quad (5)$$

The halo mass is in units of  $10^9 M_\odot$ , the radius is in units 6 kpc. As we will see later this value is too low for the explanation of efficient BH growth. This estimation differs greatly from the real density in halo center in some cases. Following [18] a halo is considered composed of DM spherical isothermal halo and a disc of baryon matter. The latter is supported by the angular momentum of the system. In this case the density of particles in the centre of halo increases by several orders. The numerical value is presented in [19]:

$$n = 6 \times 10^4 f_d^2 \lambda_{0.05}^{-4} T_{\text{gas},8000}^{-1} R_{\text{vir},6}^{-4} M_{h,9}^2 \text{ cm}^{-3}. \quad (6)$$

Here  $f_d$  is the fraction of gas in the disc (normalized to 0.5) and  $\lambda$  is the spin parameter in units of 0.05. The latter value should be considered accurately. In demonstrates that a halo gave an angular momentum. The initial cosmological perturbations are vortex free and the general question arises: how fast do  $\lambda$  grow (together with discs). The work [20] states fast disc creation for the case of atomic cooling: when the temperature exceeds  $T > 10^4$  K atomic cooling became so efficient that it keeps  $T = 10^4$  K and satisfy  $t_{\text{cool}} < t_{\text{dyn}}$ , these conditions lead to fast near isothermal gas collapse. The

condition of the disc stability  $\lambda > \lambda_{\text{crit}}$  diminishes low values of  $\lambda$ . According to [21] the average value of the spin parameter is  $\bar{\lambda} = 0.05$ . We will use approximation (5) for  $n$  when  $T < 10^4$  K and (6) when  $T > 10^4$  K (setting then by hands the temperature  $T = 10^4$  K). But we consider this fact to be carefully analysed.

To make an evaluation of BH growth we should know the dependence of  $M_{\text{halo}}(z)$ . To calculate all parameters of halos we will use the Press–Schechter formalism, see [1]. First step is the calculation of the variance

$$\sigma^2(M) = \sigma^2(R) = \int_0^\infty \frac{dk}{2\pi} k^2 P(k) \left[ \frac{3j_1(kR)}{kR} \right]^2, \quad (7)$$

where  $M = 4\pi\rho_m R^3/3$  and  $\rho_m$  is the mean density of matter in the Universe,  $P(k)$  is a power spectrum of density perturbations. We will use the approximation for this spectrum proposed by [22] (the paper is accompanied by the code to calculate the integral (7)).

Using the growth factor  $D(z)$  (normalized as  $D(0) = 1$ , so for clearance we omit constant factors in  $D_1$  definition):

$$D(z) = \frac{D_1(z)}{D_1(0)}, \quad D_1(z) = g(z)^{1/2} \int^z \frac{1+z'}{g(z')^{3/2}} dz', \quad (8)$$

$$g(z) = \Omega_0(1+z)^3 + (1 - \Omega_0 - \Omega_\Lambda)(1+z^2) + \Omega_\Lambda, \quad (9)$$

the critical overdensity of a collapsed cloud can be calculated according to the top-hat model:

$$\delta_{\text{crit}} = \frac{1.686}{D(z)}. \quad (10)$$

The solution of the equation

$$\delta_{\text{crit}}(z) = n\sigma(M) \quad (11)$$

gives the dependence  $M(z)$  for the collapsed cloud with the  $n\text{-}\sigma$  Gaussian fluctuation. This model is very simplified but quite exactly reproduces history of halo merges. The result of calculation is presented on Fig. 1. We will use this dependence as a basis for analytical estimation of BH growth.

The Bondi–Hoyle accretion rate (4) is limited by some physical effects that reduce the rate of accretion. First the Bondi radius should not exceed geometrical parameters of halos: the halo virial radius. The latter is calculated using known  $M_{\text{halo}}$ :

$$R_{\text{Bondi}} < R_{\text{vir}} = \left( \frac{3}{4\pi} \frac{M_{\text{halo}}}{18\pi^2 \rho_m} \right)^{1/3}, \quad (12)$$

with  $18\pi^2$  is an overdensity at collapse redshift. So the cross-section mentioned before should not exceed  $\sigma_{\text{max}} = \pi R_{\text{vir}}^2$ . And the disc thickness when the latter is formed. From [20] we have:

$$R_{\text{Bondi}} < H_{\text{disc}} = \frac{c_s}{\sqrt{4\pi G \mu m_p n_0}}. \quad (13)$$

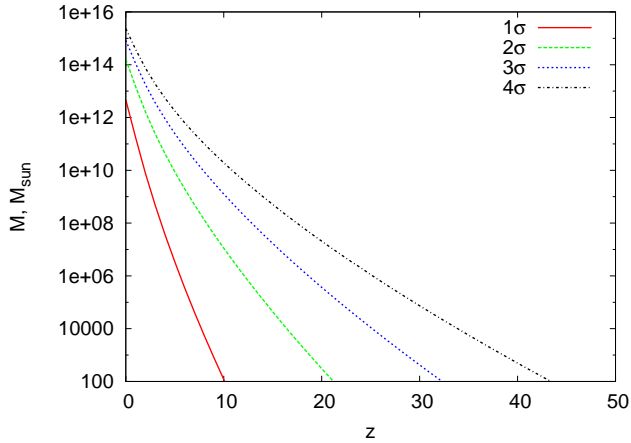


FIG. 1: Halo mass vs redshift according to Press-Schechter model for different fluctuations.

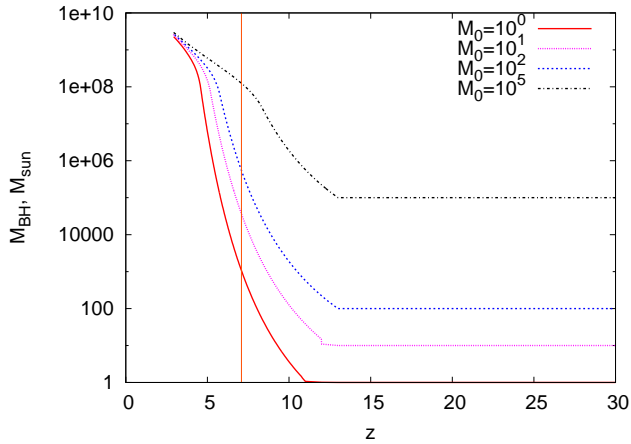


FIG. 2: Dependence of a black hole mass vs redshift. The vertical line is at  $z = 7.085$ .

The second limitation is the Eddington accretion rate (when the falling matter rate is limited by the radiation push):

$$\dot{M}_{\text{Edd}} = \frac{1}{\epsilon} \frac{M_{\text{BH}}}{t_{\text{Salp}}}, \quad t_{\text{Salp}} = \frac{c\sigma_T}{4\pi G m_p} \sim 450 \text{ Myr}. \quad (14)$$

Typical value of radiation efficiency is  $\epsilon \approx 0.1$ . This rate is also the upper limit of  $\dot{M}_{\text{BH}}$ .

The results of BH growth from 3- $\sigma$  fluctuations in the Press-Schechter formalism are shown on Fig. 2 for several initial BH masses:  $M_0 = 10^0 \div 10^2 M_\odot$  – BH seeds from massive PopIII stars,  $M_0 = 10^5 M_\odot$  – a direct collapse in metal-free galaxies, see [23]. The BH mass starts to grow significantly only after a baryon disc creation. It quickly sets at the Eddington rate and further decrease ( $z \approx 5 - 10$ ) of growth rate is connected with the  $R_{\text{Bondi}} < H_{\text{disc}}$  criterium. Our calculation shows that it is not so simple even though impossible to obtain  $M_{\text{BH}} \approx 10^9 M_\odot$  at  $z = 7$ . We could consider as example the case of 5- $\sigma$  fluctuation in PS, see Fig. 3,

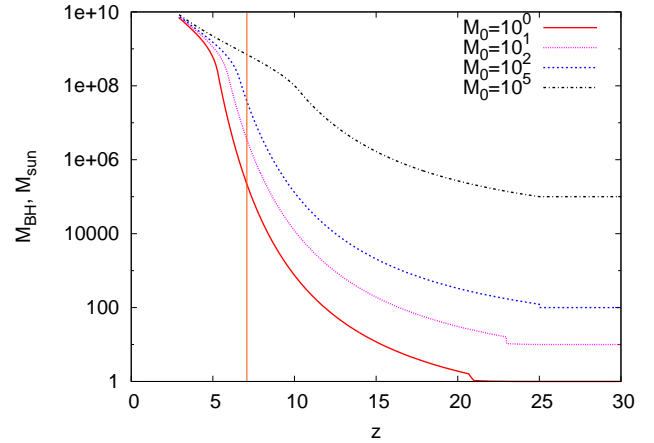


FIG. 3: Dependence of a black hole mass vs redshift, 5- $\sigma$

and see that is hardly saves the situation. The reason could be simply described in the following way: for 3- $\sigma$  fluctuations the active growth starts at  $z \approx 11 - 13$  and is limited to the Eddington rate. From  $z = 13$  till  $z = 7$  we have  $\approx 340$  Myr, so  $\exp(340/45) \sim 2 \times 10^3$ . So the BH should be initially extremely massive to reach  $10^9 M_\odot$ . These results are made with rough approximation, but we believe that they reproduce the general properties of considered processes.

The mass of the quasar from [16] is explained in more sophisticated simulations by [13] with account for hydrodynamics, star formation and feedback, for details see [10]. In those simulations galaxies were created as initial conditions with nonzero angular momentum. As was said earlier it requires careful analysis.

As a result of this section we could state that creation of a supermassive black hole at high redshifts is a difficult task. Though all known objects now are likely to be described by simulations, the assumption of existence of a primordial black hole with large mass could simplify the explanation and for more distant BHs, probably be discovered in future, it could be the only possible explanation. The PBBH changes nucleosynthesis around itself. More metals are created and it accelerates the process of local evolution, and intensive growth could start earlier, at  $z > 13$  (for 3- $\sigma$ , from results of our calculations), this gives more time for the BH growth with the Eddington rate. This is the general reason why PBBHs are good candidates for dinosaurs.

#### IV. CONCLUSIONS

The aim of the paper is to introduce the conception of “cosmological dinosaurs” – objects appeared long before the period of intensive structure formation according to the standard model. The necessity for them could arise in future: the observations are discovering now more and more distant galaxies and quasars with no end in sight.

At some moment this “flow” of newly opened objects could contradict the accepted theory. We consider in this case that the number of additional discoveries will be very small, so only light extension of the theory is necessary. In our work the appearance of such objects is connected with primordial big black holes (PBBHs, we propose to introduce this term as rich cosmological physics is connected with them). From our point of view these are the most natural and simple extension: they start to form the structure around themselves much earlier. The exact quantitative contribution could be calculated in more sophisticated models, than presented in this paper (e.g.

with account for hydrodynamics) and is planned in future works. In the framework of our model we have shown that modern high-redshift objects are on the edge of the standard theory predictions. So the discoveries of dinosaurs or effects of their previous appearance could be made in the nearest future, introducing good probes for new physics in the early Universe.

SIG is partly supported by the project “Development of ultrahigh sensitive receiving systems of THz wavelength range for radio astronomy and space missions” in NSTU n.a. R.E. Alekseev, LCN.

- 
- [1] R. Barkana and A. Loeb, *Physics Reports* **349**, 125 (2001), arXiv:astro-ph/0010468.
  - [2] M. D. Lehnert et al., *Nature* **467**, 940 (2010), 1010.4312.
  - [3] R. J. Bouwens et al., *Nature* **469**, 504 (2011), 0912.4263.
  - [4] Á. Bogdán, W. R. Forman, I. Zhuravleva, J. C. Mihos, R. P. Kraft, P. Harding, Q. Guo, Z. Li, E. Churazov, A. Vikhlinin, et al., *ApJ* **753**, 140 (2012), 1203.1641.
  - [5] E. Caffau, P. Bonifacio, P. François, L. Sbordone, L. Monaco, M. Spite, F. Spite, H.-G. Ludwig, R. Cayrel, S. Zaggia, et al., *Nature* **477**, 67 (2011).
  - [6] E. Komatsu, J. Dunkley, M. R. Nolte, C. L. Bennett, B. Gold, G. Hinshaw, N. Jarosik, D. Larson, M. Limon, L. Page, et al., *The Astrophysical Journal Supplement Series* **180**, 330 (2009), 0803.0547.
  - [7] V. Springel, S. D. M. White, A. Jenkins, C. S. Frenk, N. Yoshida, L. Gao, J. Navarro, R. Thacker, D. Croton, J. Helly, et al., *Nature* **435**, 629 (2005), arXiv:astro-ph/0504097.
  - [8] S. E. Woosley, A. Heger, and T. A. Weaver, *Reviews of Modern Physics* **74**, 1015 (2002).
  - [9] N. Yoshida, V. Bromm, and L. Hernquist, *The Astrophysical Journal* **605**, 579 (2004), arXiv:astro-ph/0310443.
  - [10] V. Springel, T. Di Matteo, and L. Hernquist, *MNRAS* **361**, 776 (2005).
  - [11] T. H. Greif, J. L. Johnson, R. S. Klessen, and V. Bromm, *Monthly Notices of the Royal Astronomical Society* **387**, 1021 (2008), 0803.2237.
  - [12] V. Bromm and N. Yoshida, *The Annual Review of Astronomy and Astrophysics* **49**, 373 (2011), 1102.4638.
  - [13] T. Di Matteo, N. Khandai, C. DeGraf, Y. Feng, C. Croft R. A., J. Lopez, and V. Springel, *ApJ* **745**, L29 (2012).
  - [14] S. L. Finkelstein, C. Papovich, M. Giavalisco, N. A. Reddy, H. C. Ferguson, A. M. Koekemoer, and M. Dickinson, *The Astrophysical Journal* **719**, 1250 (2010), 0912.1338.
  - [15] M. Y. Khlopov, *Research in Astronomy and Astrophysics* **10**, 495 (2010), 0801.0116.
  - [16] D. J. Mortlock, S. J. Warren, B. P. Venemans, M. Patel, P. C. Hewett, R. G. McMahon, C. Simpson, T. Theuns, E. A. González-Solares, A. Adamson, et al., *Nature* **474**, 616 (2011), 1106.6088.
  - [17] H. Bondi and F. Hoyle, *MNRAS* **104**, 273 (1969).
  - [18] H. J. Mo, S. Mao, and S. D. M. White, *Monthly Notices of Royal Astronomy Society* **295**, 319 (1998), arXiv:astro-ph/9707093.
  - [19] M. Volonteri and M. J. Rees, *The Astrophysical Journal* **633**, 624 (2005), arXiv:astro-ph/0506040.
  - [20] S. P. Oh and Z. Haiman, *The Astrophysical Journal* **569**, 558 (2002), arXiv:astro-ph/0108071.
  - [21] S. Warren M, J. Quinn P, K. Salmon J, and H. Zurek W, *MNRAS* **399**, 405 (1992).
  - [22] D. J. Eisenstein and W. Hu, *The Astrophysical Journal* **511**, 5 (1999), arXiv:astro-ph/9710252.
  - [23] M. C. Begelman, M. Volonteri, and M. J. Rees, *MNRAS* **370**, 289 (2006), arXiv:astro-ph/0602363.